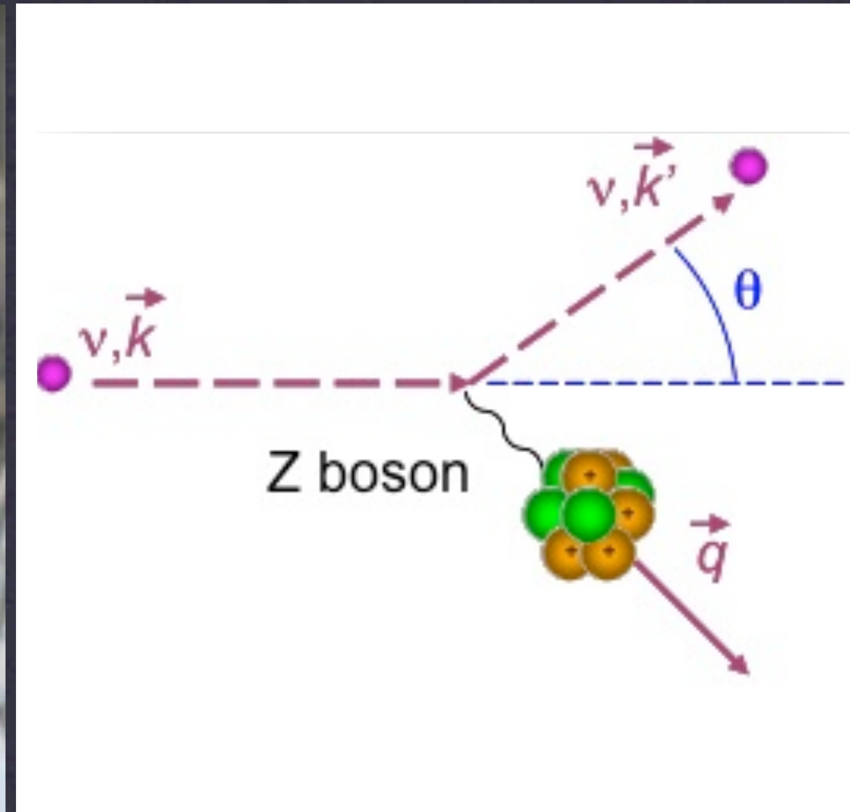
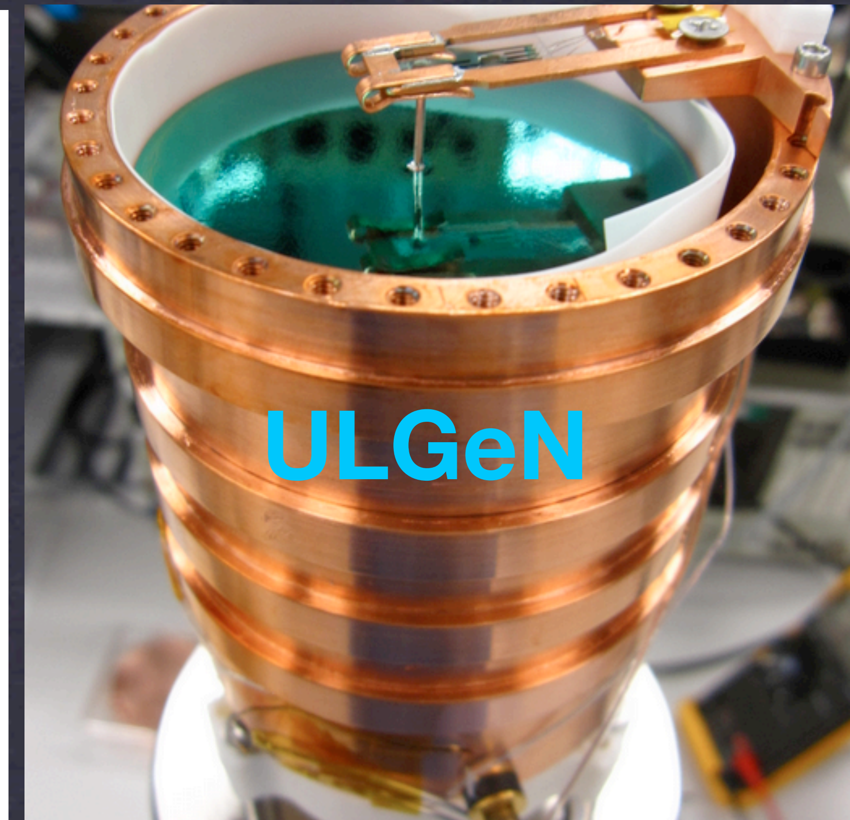
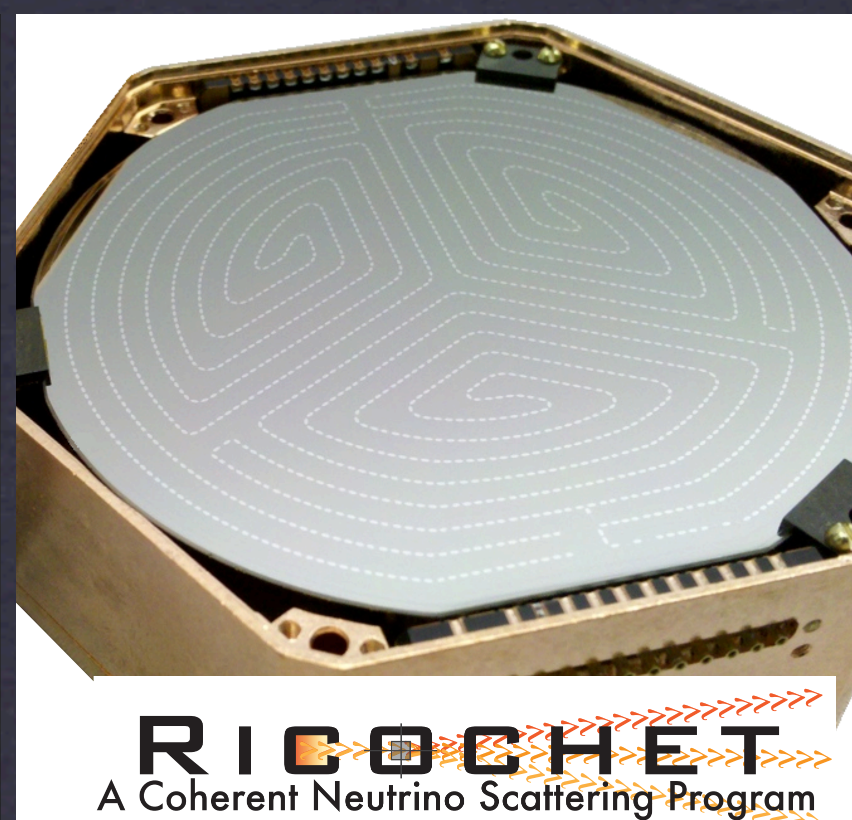
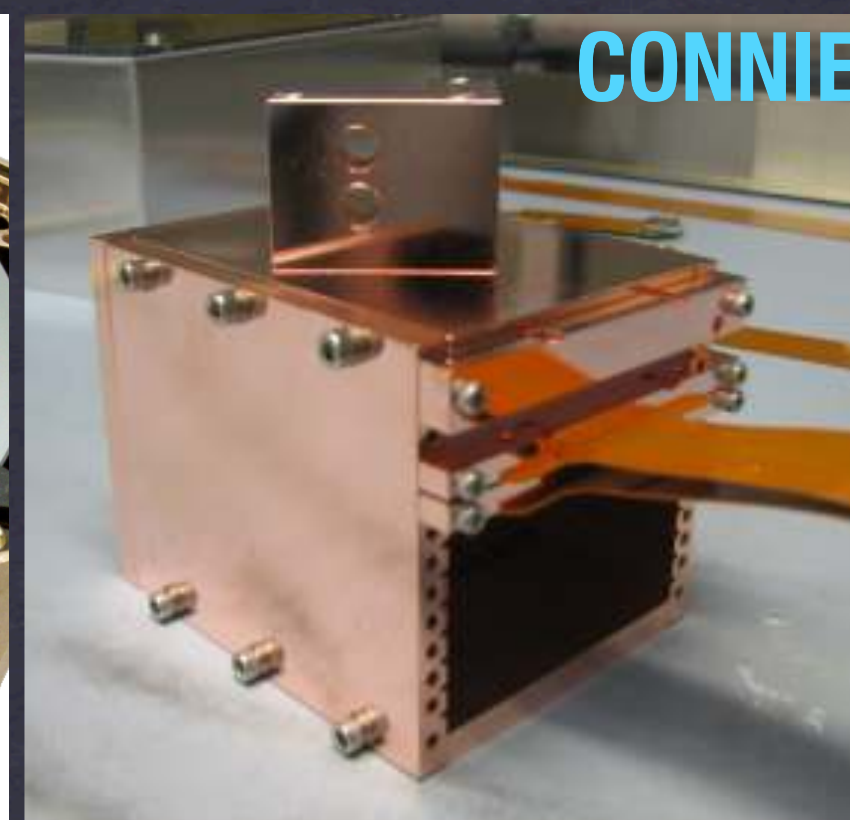




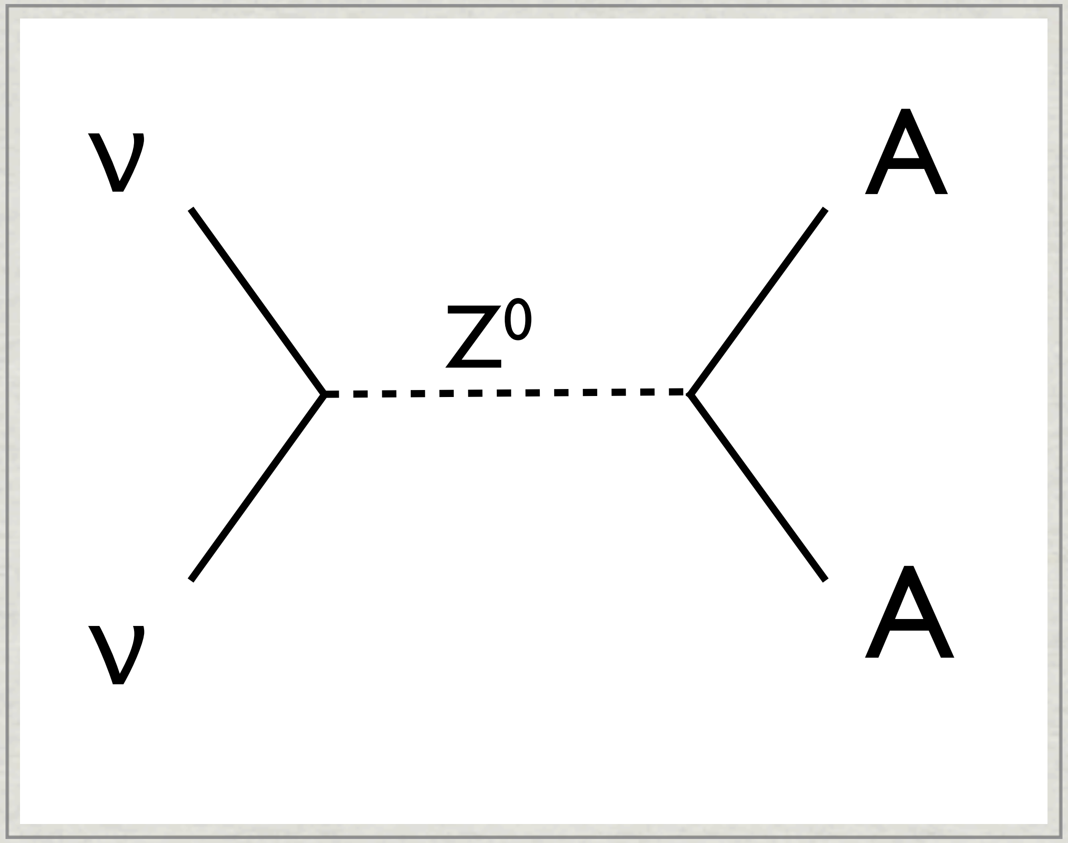




NOVEL DETECTORS & EXPERIMENTS AT REACTORS

PHIL BARBEAU, STANFORD UNIVERSITY

Coherent ν - Nucleus Scattering



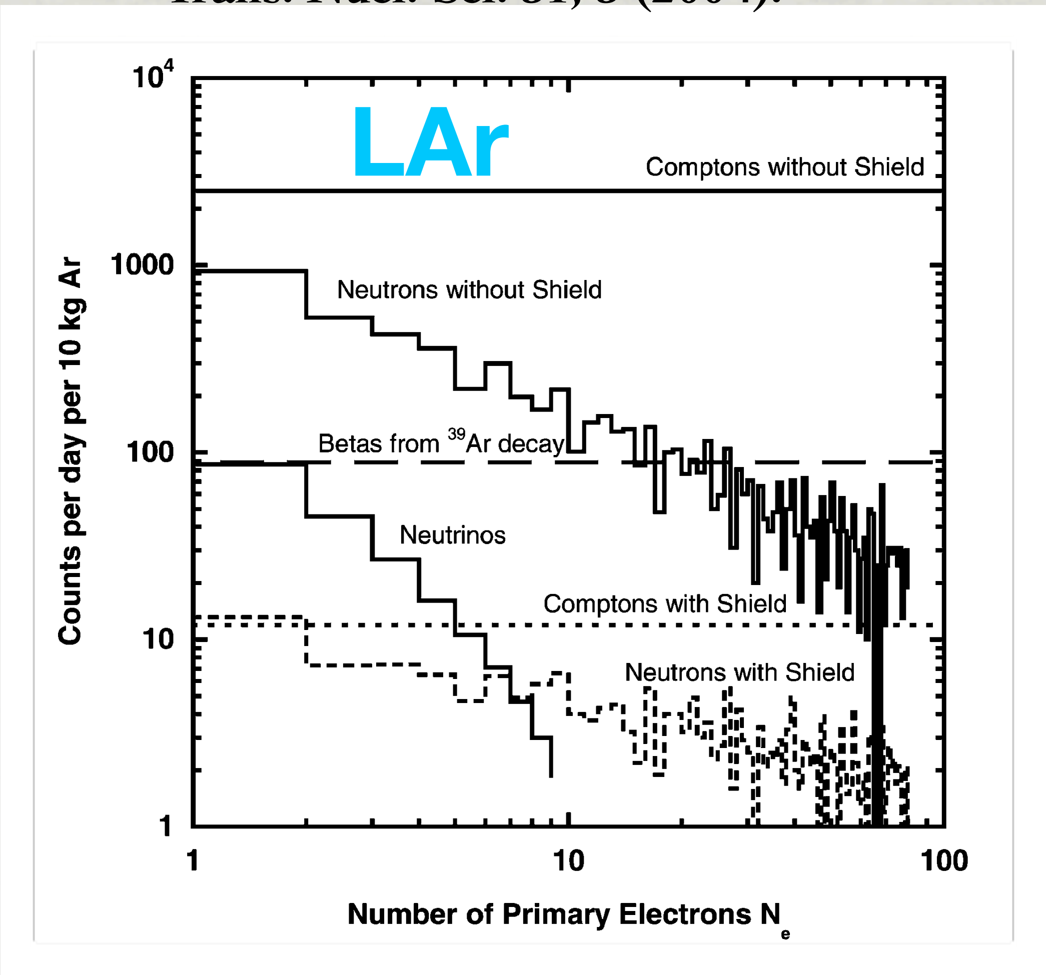
D. Z. Freedman, PRD 9 (5) 1974

- As yet ***unobserved*** Standard Model process: analogous to coherent forward scattering of e+A→e+A. Predicted in 1974 with the realization of the weak neutral current
- Scatters coherently off all nucleons → cross-section enhancement $\sigma \propto N^2$
- Requires identical initial & final nuclear states → neutral current elastic scattering
- Nucleons must recoil <u>in phase</u> → low momentum transfer qR < 1→ ***sub-keV recoil***
- E_ν < 10's of MeV for most nuclei
- Long predicted to have neutrino technology and fundamental physics applications

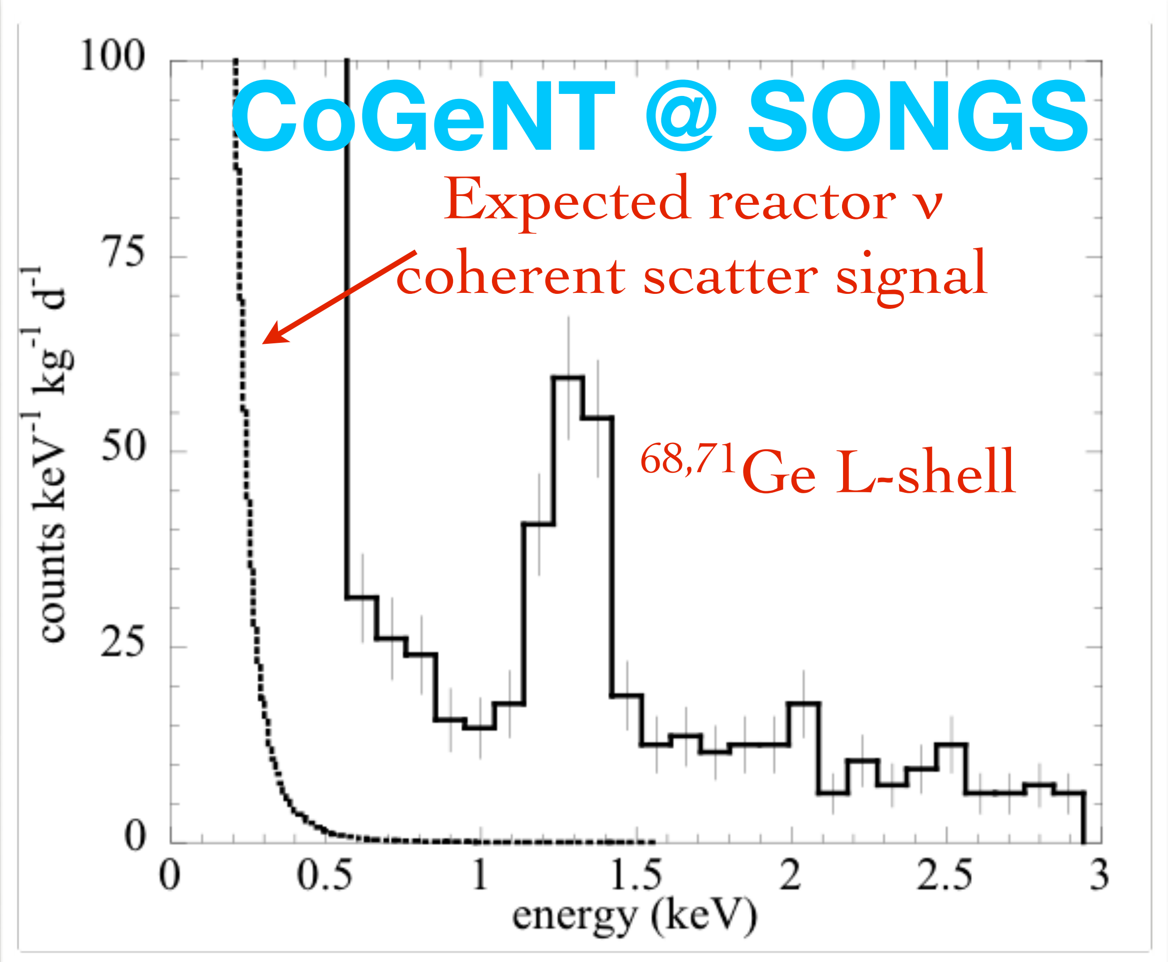
Reminder: what it takes

- Low threshold
- Low backgrounds
- Order kg mass

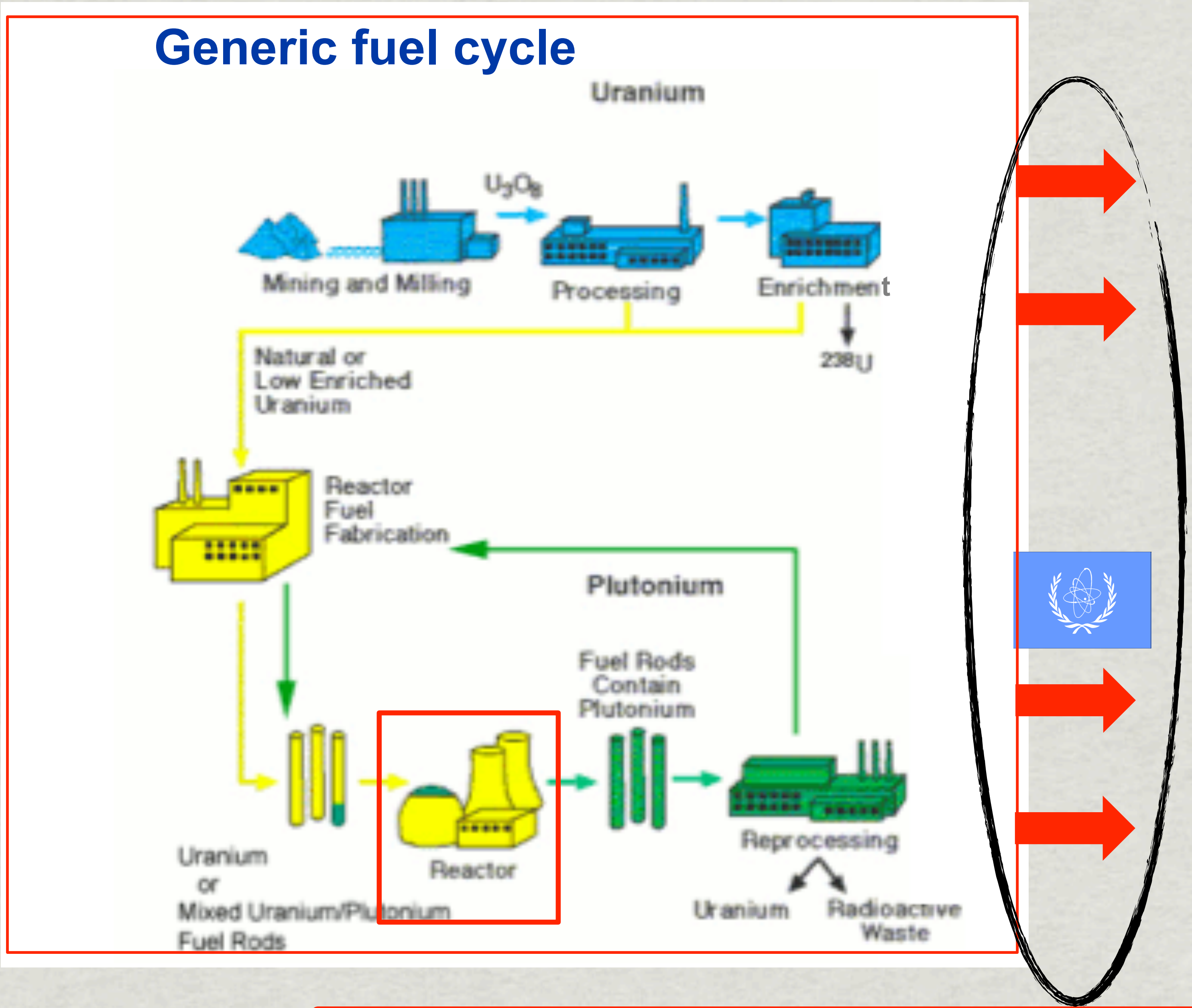
C. Hagmann, A. Bernstein, Trans. Nucl. Sci. 51, 5 (2004).

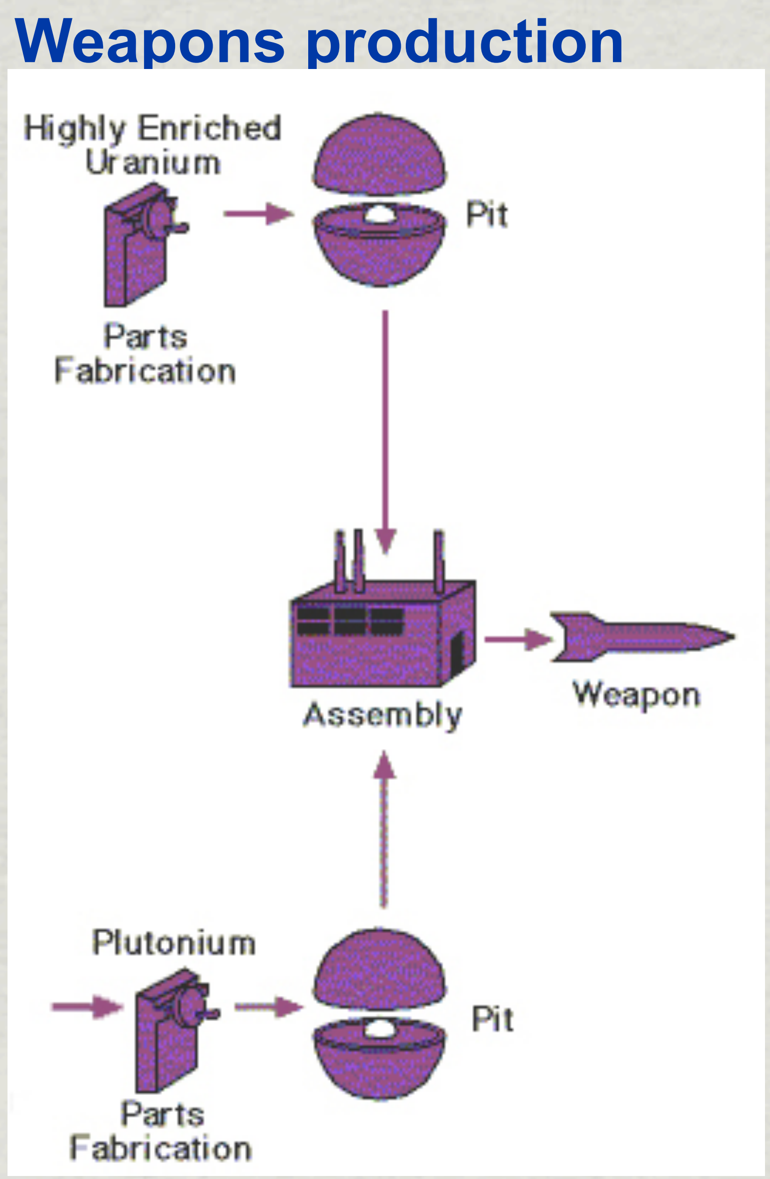


PPC detectors: P. S. Barbeau, J. I. Collar, and O. Tench., JCAP, 2007(09):009, 2007.



The IAEA ‘Safeguards’ regime monitors the flow of fissile material through the nuclear fuel cycle in 170 countries





Goal for antineutrino measurements - track fissile inventories in operating reactors

A. Bernstein, Meeting on Coherent Neutrino Scattering, 2012

Things the IAEA would like, ways CNNS could *conceivably* help

1. Power monitoring for a subset of reactors under safeguards (usually research reactors)
2. Ensuring that certain reactor fuels (MOX) have achieved a desired level of burnup/irradiation
3. Improve the level of precision and independence regarding fissile mass of discharged reactor fuel
4. Monitor multiple reactors with one detector
5. Long range monitoring or exclusion of reactors

Smaller footprint counting detectors with competitive statistics
– 100s of cpd

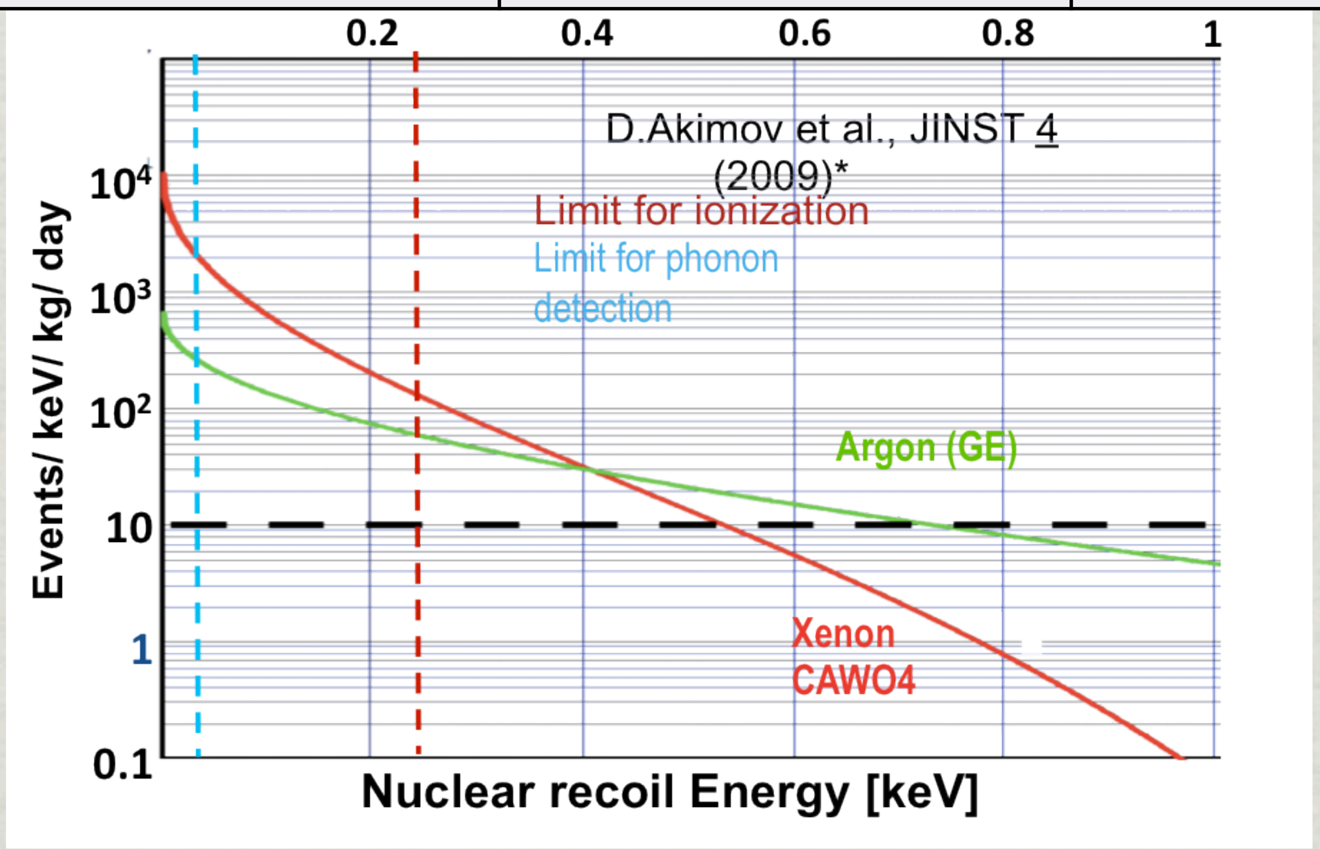
Detectors capable of deconvolving the reactor energy spectrum
-1000s of cpd

Detectors with directional sensitivity
??

A. Bernstein, Meeting on Coherent Neutrino Scattering, 2012

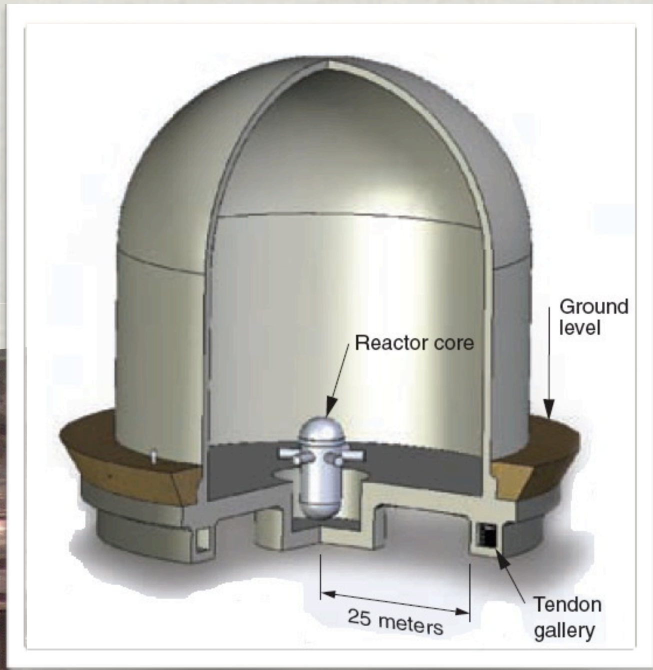
Coherent scatter counting detectors

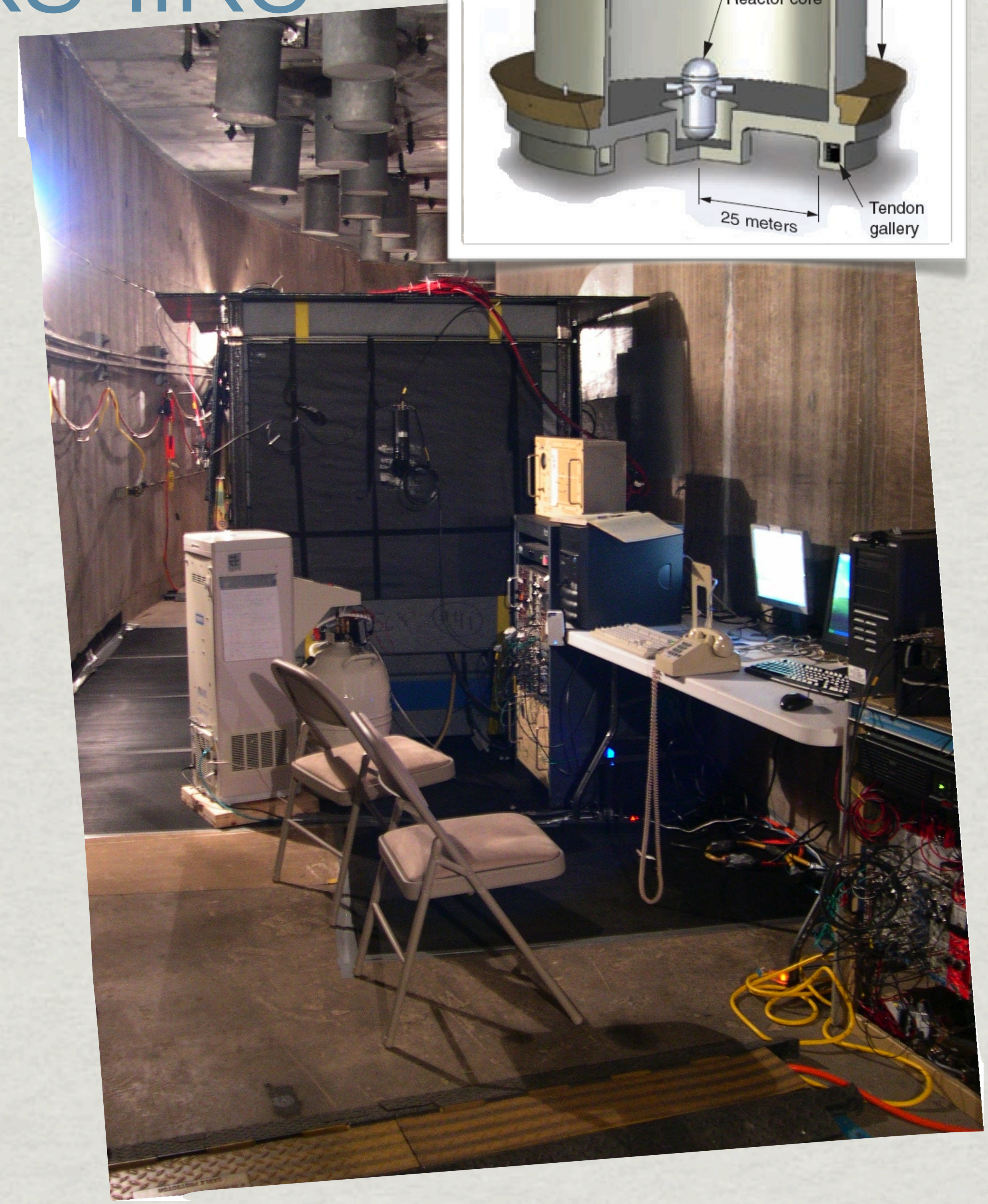
	Argon	Germanium	Phonon-counter
Footprint with cryo and shield	$(1.5\ m)^3$	$(1.5\ m)^3$??	$(0.5\ m)^3$??
Mass to get 100 cpd @ 25 m, 3 GWt	10-15 kg (> 2 e^- sensitivity, depends on quench factor)	4-5 kg (100 eV threshold)	50 gram (~50 eV threshold)
Cost	100-200K	?	?



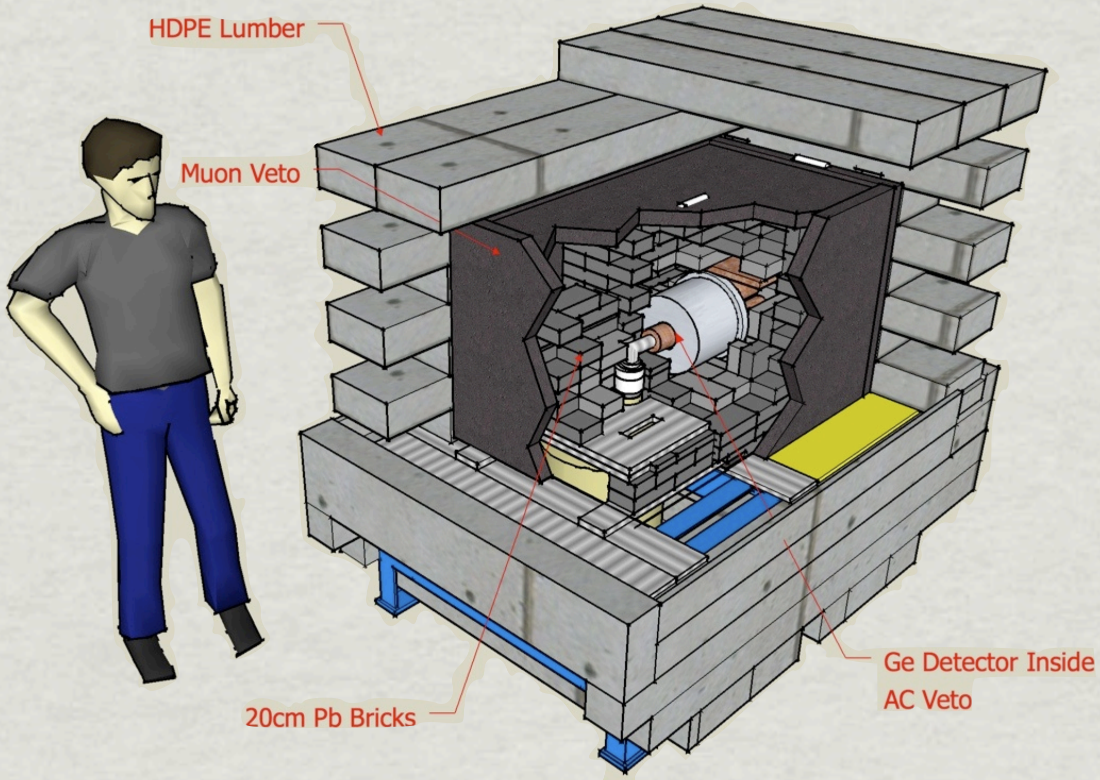
A. Bernstein, Meeting on Coherent Neutrino Scattering, 2012

CoGeNT: what a deployment looks like





- Deployed the CoGeNT detector to the San Onofre Nuclear Generating Station (SONGS)
- Tendon Gallery (30 m.w.e.) modest protection from atmospheric cosmic-ray backgrounds



CoGeNT: what a deployment looks like

- Deployed th
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- Tendon Galle
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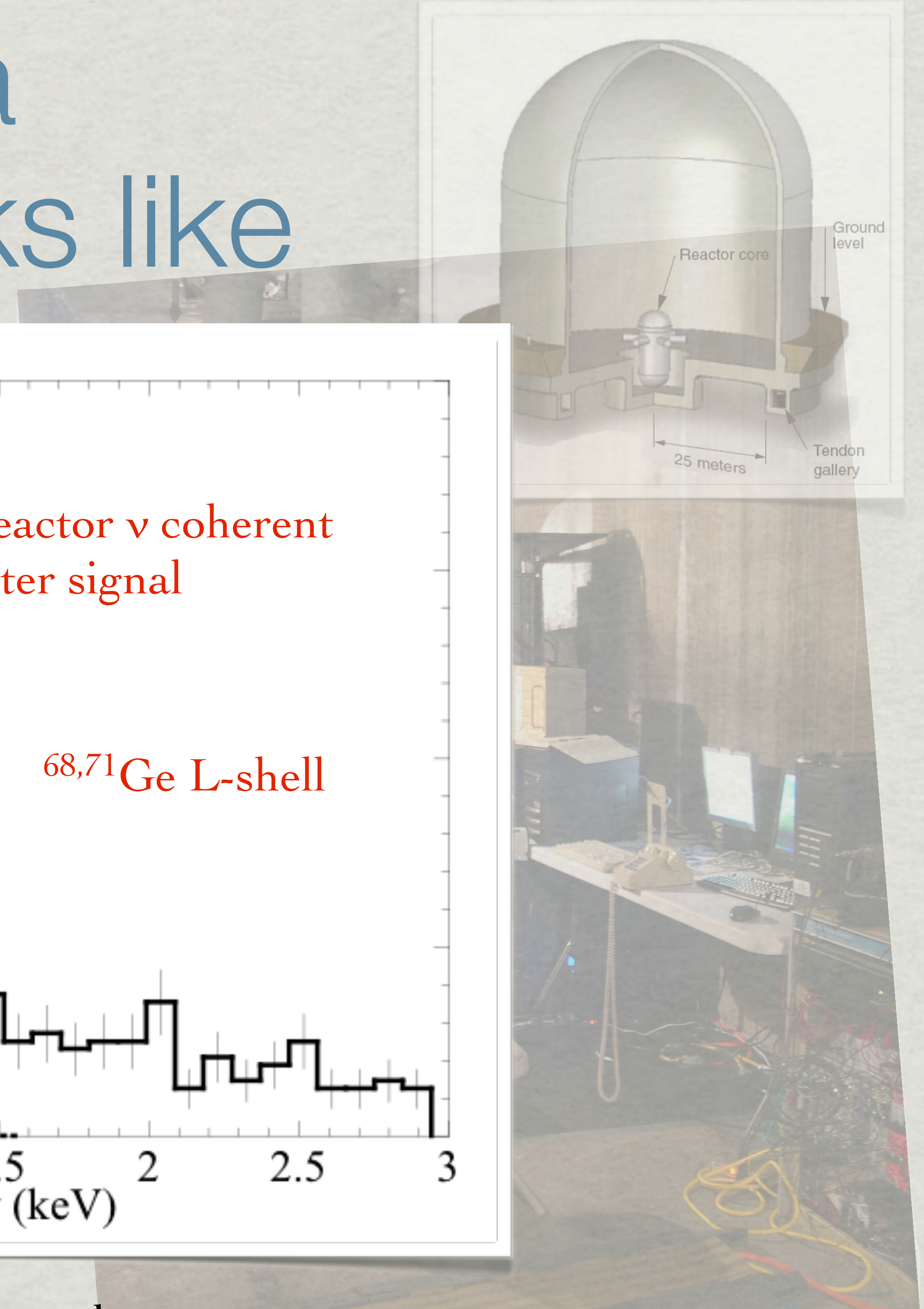
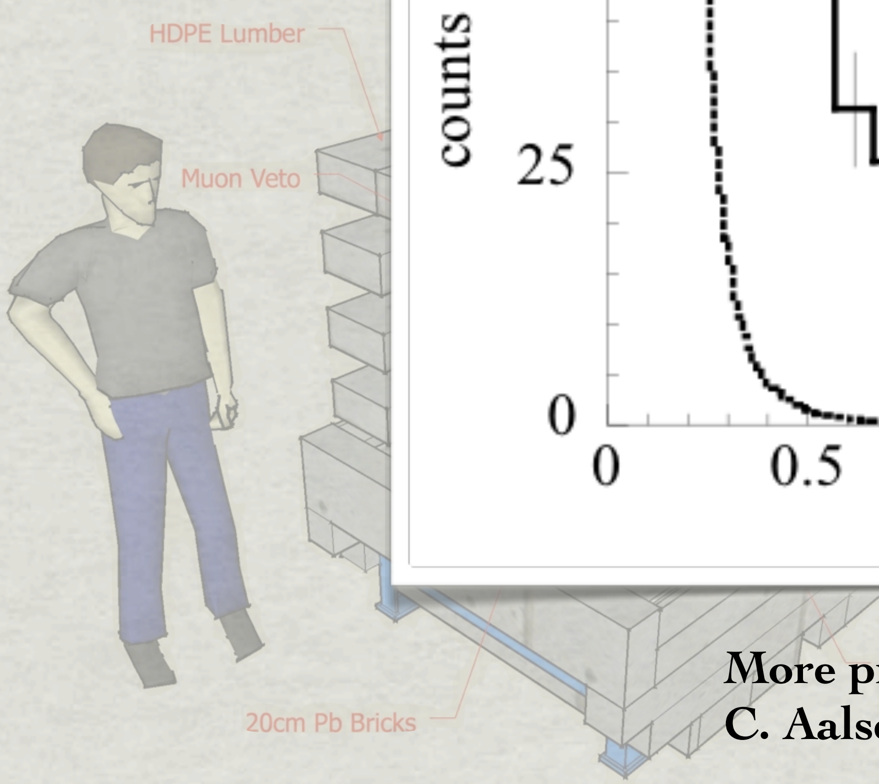
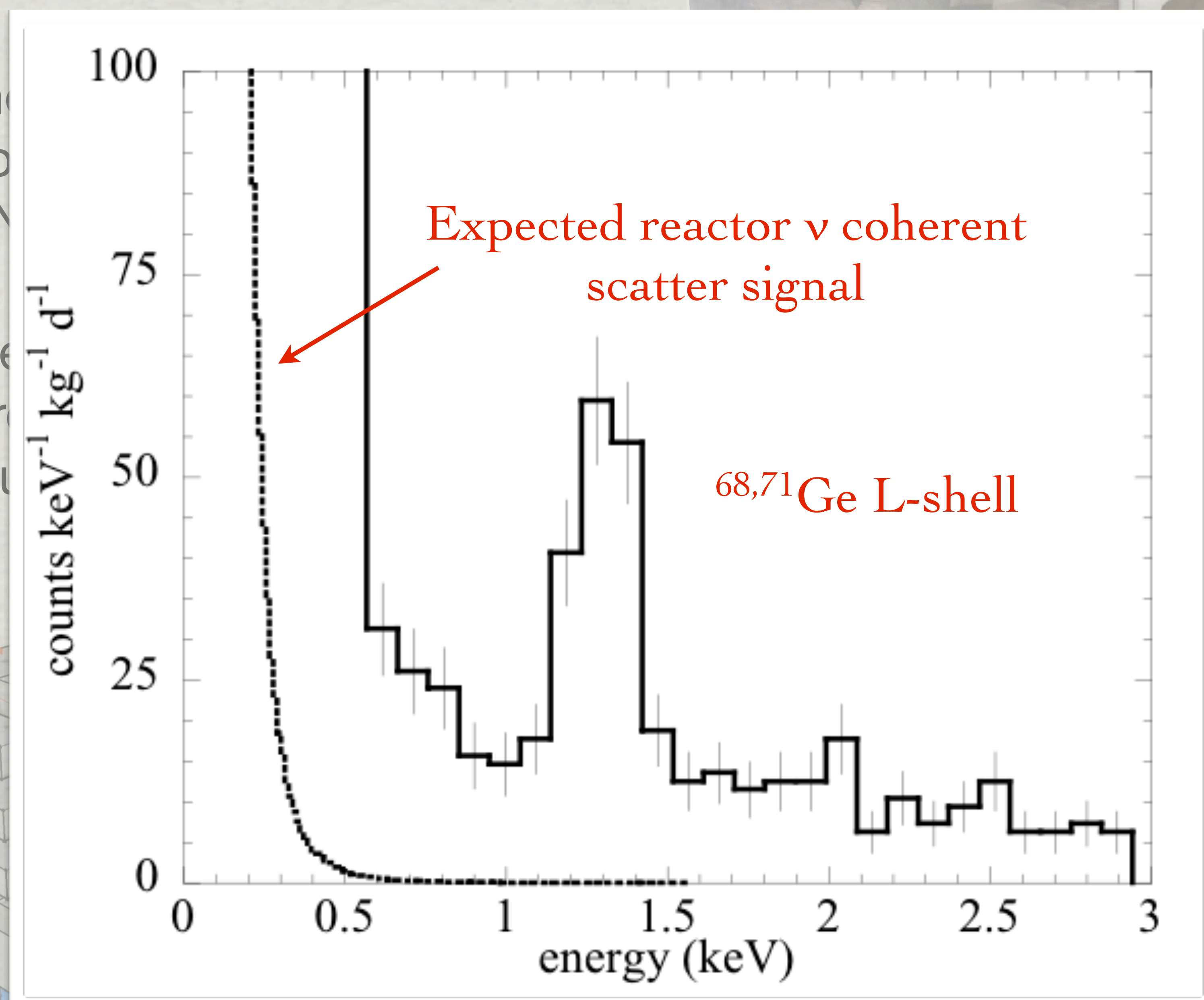






More progress on backgrounds at:
C. Aalseth, P. S. Barbeau, J. Colarisi, et al., arXiv:1208.5737

Precision Test of the Weak Nuclear Charge

- Coherent cross-section proportional to Q_W^2
- A precision measurement of the coherent scattering cross section is a sensitive test of radiative corrections due to new physics above the weak scale (**Technicolor, Z'**, etc.)

L. M. Krauss, PLB 269, 407

$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ \underline{sin^2\theta_w} - 1) + N)^2$$

+ axial vector factors which have largest theoretical uncertainty (strong quark contributions, weak magnetism term, effective neutrino charge radii)

Precision Test of the Weak Nuclear Charge

3) Factorize out ν flux (~6%) & <u>absolute</u> rate uncertainties

→ group according Z=N & Z≠N & measure ratio: $\dfrac{R_{Z=N}}{R_{Z\neq N}}$

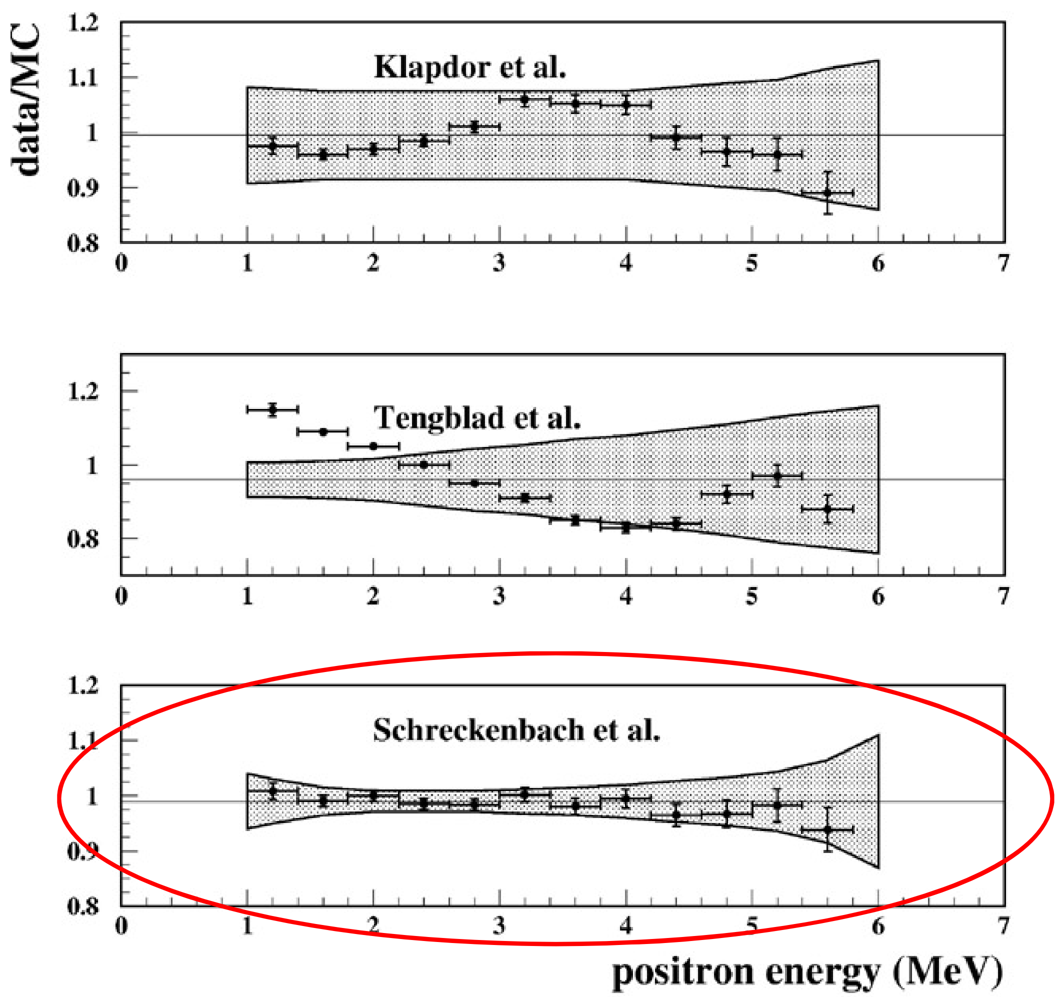
$$Q_{w,^4He} = 2 \times 4sin^2\theta_w$$
$$Q_{w,^{12}C} = 6 \times 4sin^2\theta_w$$
$$Q_{w,^{16}O} = 8 \times 4sin^2\theta_w$$
$$Q_{w,^{20}Ne} = 10 \times 4sin^2\theta_w$$

$$Q_{w,^{22}Ne} = 2 + 10 \times 4sin^2\theta_w$$
$$Q_{w,^{40}Ar} = 4 + 18 \times 4sin^2\theta_w$$
$$Q_{w,^{136}Xe} = 28 + 54 \times 4sin^2\theta_w$$

$$Q_w = N - (1 - 4sin^2\theta_w)Z$$

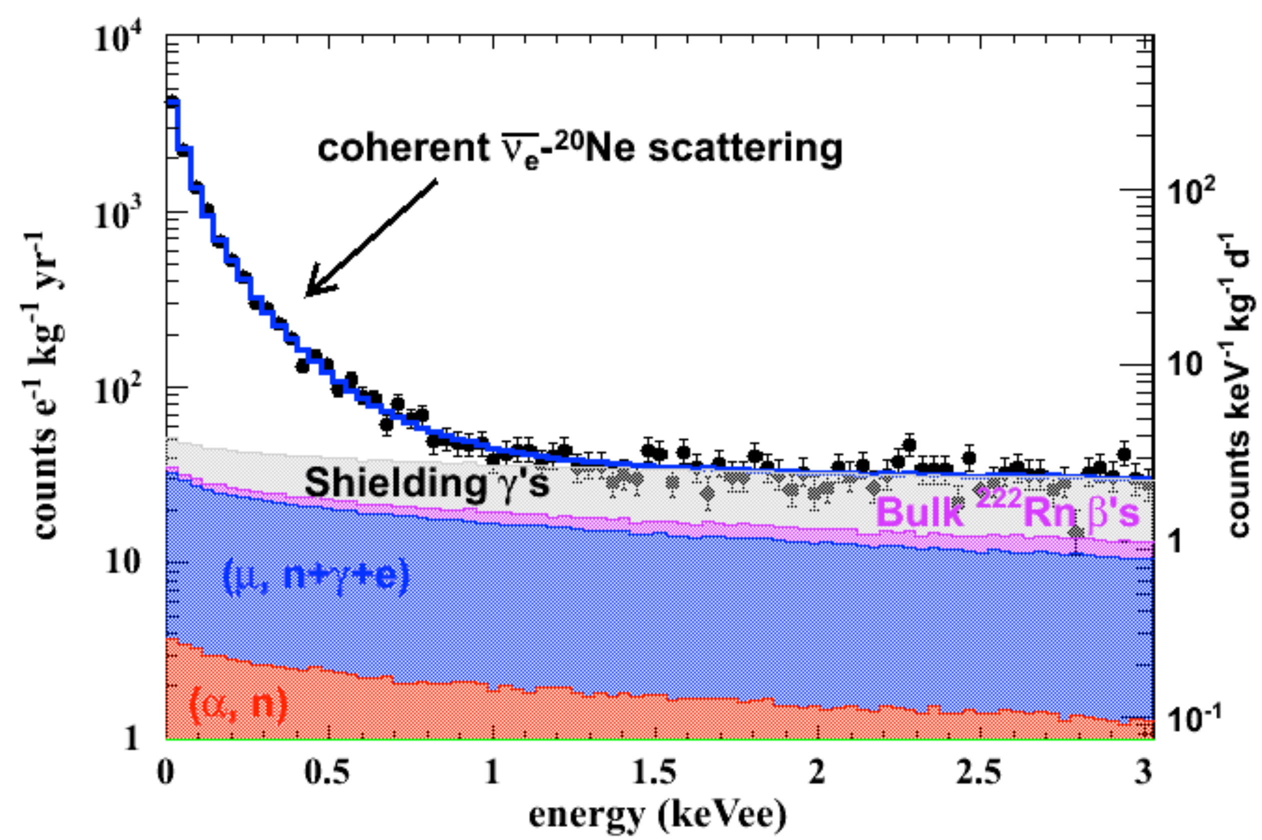
4) Use $A_1 \sim A_2$ nuclei to minimize impact of Rx neutrino spectrum uncertainties → ^{20,22}Ne

Choose recoil thresholds to select same population of ν energies (10% change between ^{20,22}Ne)



Shape verified by Bugey-3 data
Normalization improved to 1.6%

Liang Zhan SNAC, September 26–28, 2011



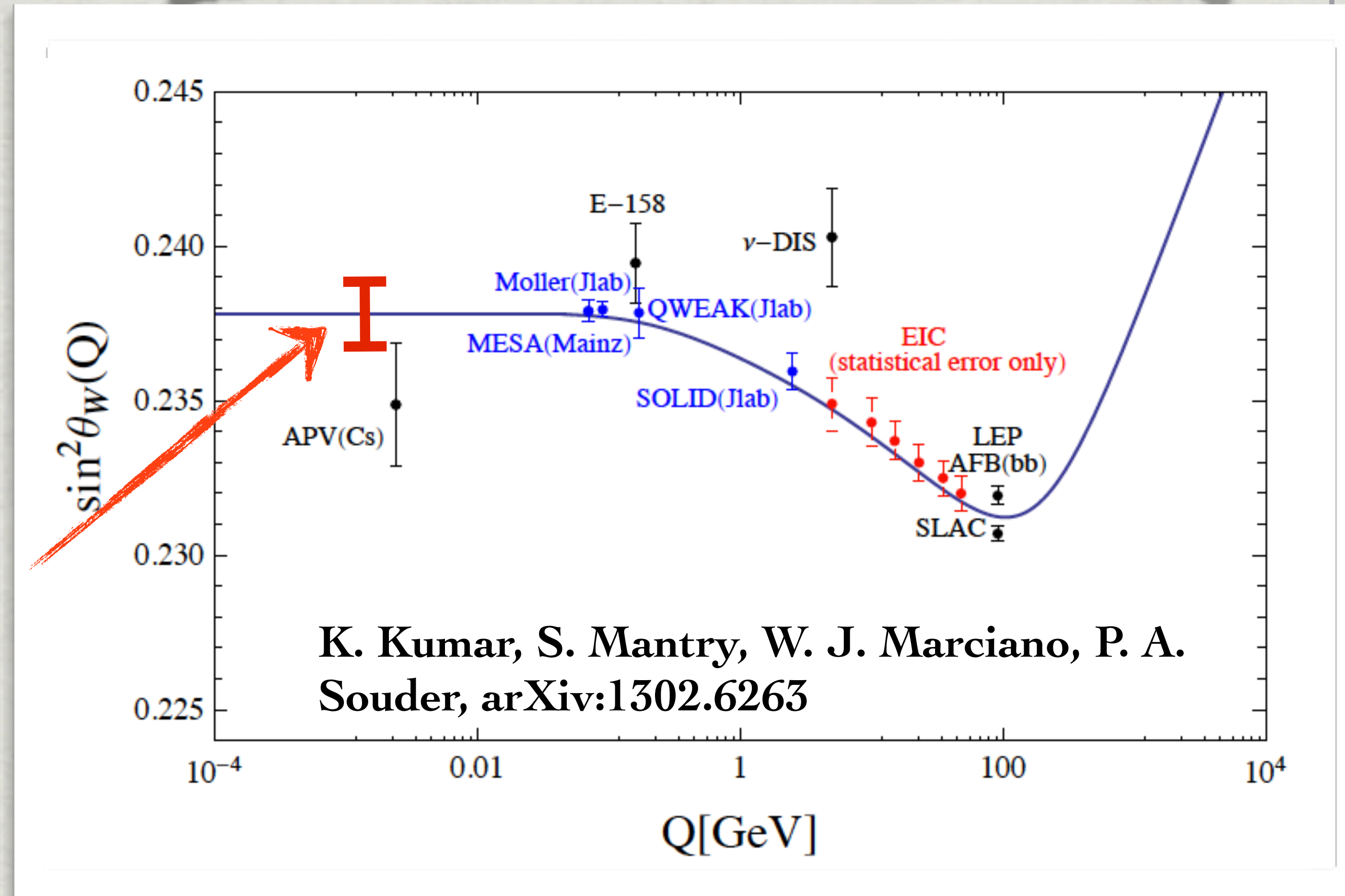
Precision Test of the Weak Nuclear Charge

$$R\left(\frac{^{22}Ne}{^{20}Ne}\right) = \frac{(2 + 10 \times sin^2\theta_w)^2}{(10 \times sin^2\theta_w)^2}$$

$$\sigma(sin^2\theta_w) = 0.57 \times \sigma R$$

- Run for 5 cycles at SONGS. One cycle is 18 months *ON*, one *OFF*
- Operate in both Tendon Galleries to maximize Rx OFF time. → 2 x 20 kg detectors at ~ 1-10 Bar
- Result → uncertainties on $\sin^2 \theta_W$:

±0.22% (stat.) ±[0.1]% (sys.) ± <0.2 (th.)

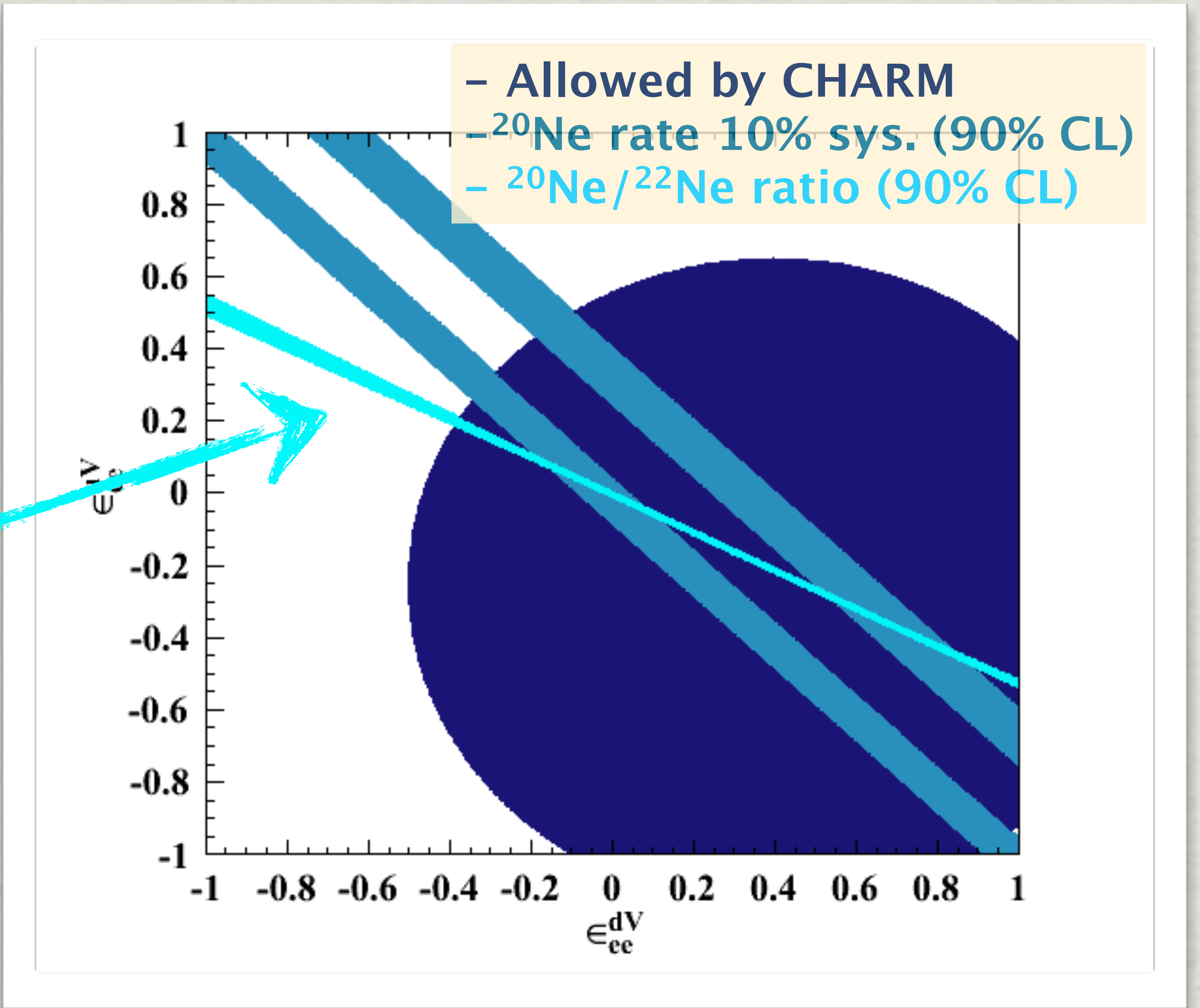


Non-Standard Interactions

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi} = G_V^2(1 + (1 - \frac{T}{E_\nu})^2 - \frac{MT}{E_\nu})$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

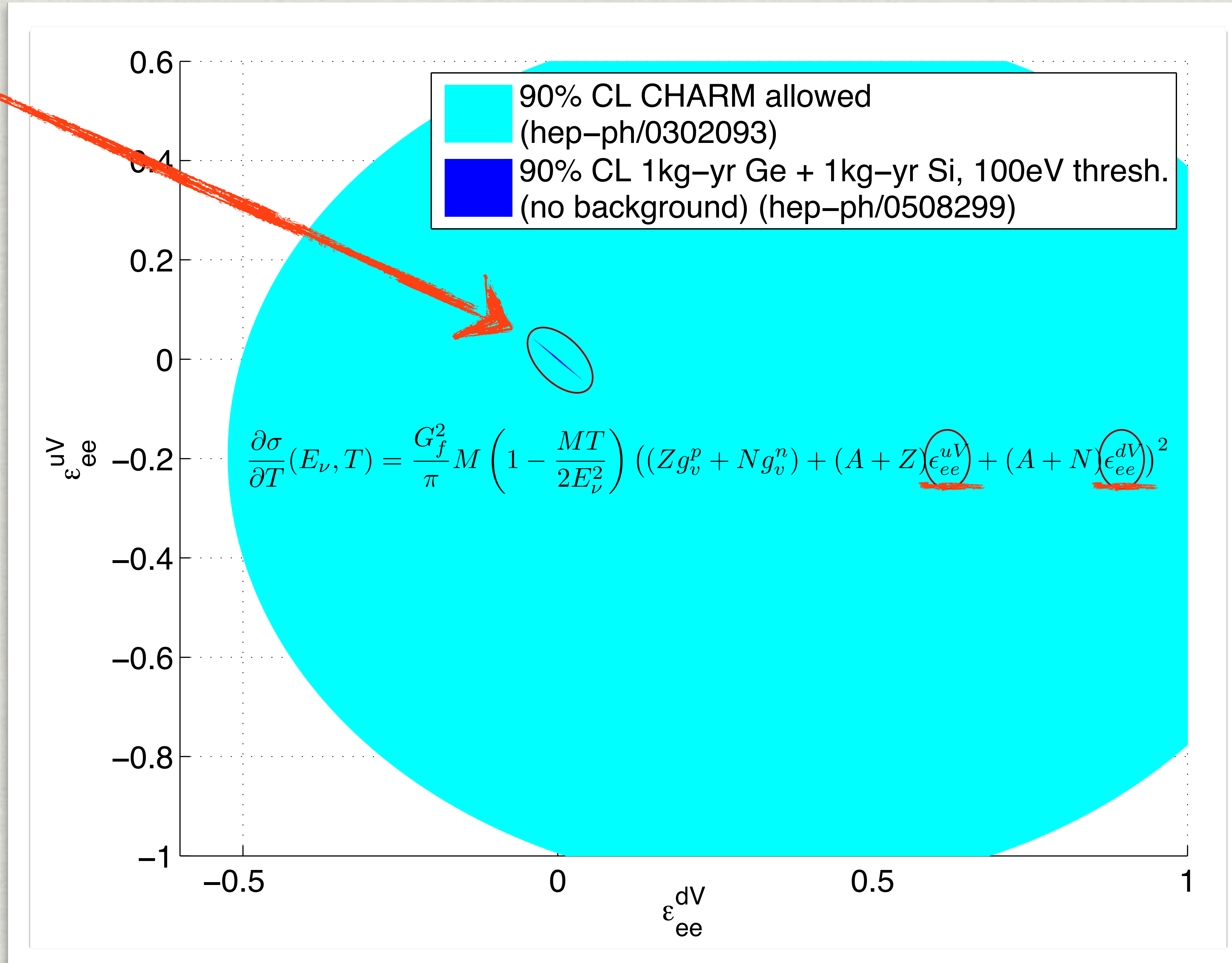
- We take advantage of the precision in the $^{20}Ne/^{22}Ne$ system
- If we include the SM radiative corrections, as well as statistical & systematic uncertainties, the ratio of the interaction rates for $^{20}Ne/^{22}Ne$ gives



also see: K. Scholberg Phys.Rev.D73:033005,2006

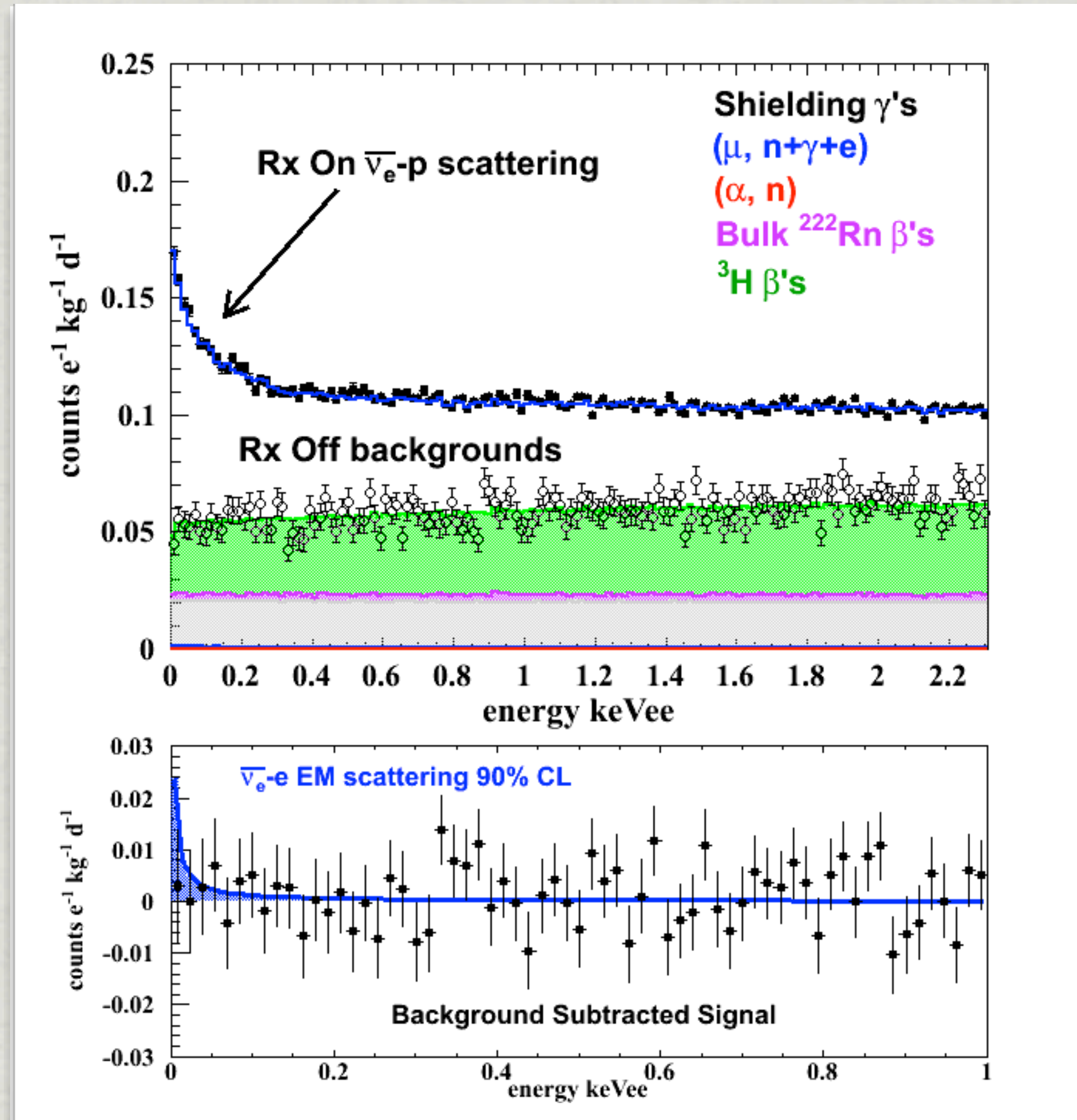
Non-Standard Interactions

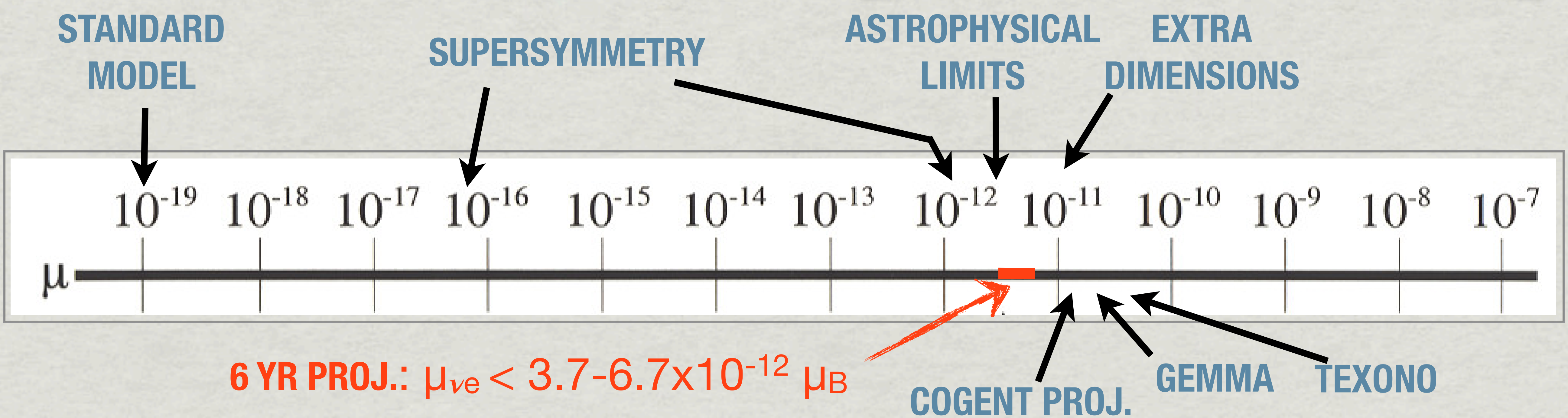
- Or, with Ricochet Ge & Si



H_2 μ_ν Search

- Pro: H_2 minimizes impact of Rx ON backgrounds from ν-nucleus scattering
- Con: ^3H background requires De-tritiation
- Uncertainties: Rx off stat.,10% QF & Rx ν flux





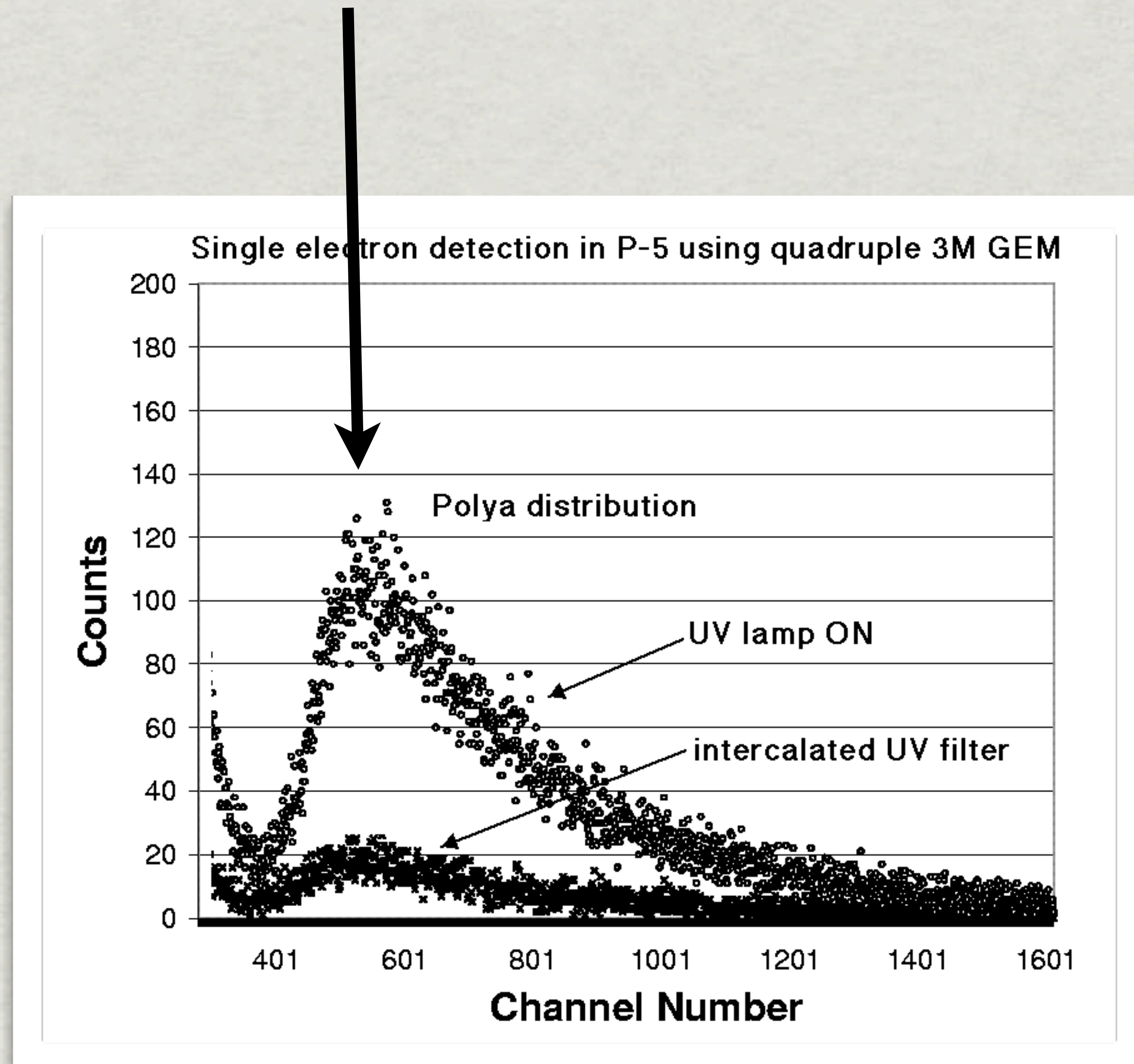
To summarize

- Application of CNNS plays role in Rx safeguards
- CNNS at Rx’s has long predicted to be Physics rich:
  - Precision tests of the weak mixing angle
  - Non-standard neutrino interactions
  - Searches for neutrino magnetic moments
  - ...Lets not forget neutral current sterile searches
- + a great deal of cross-over with Light WIMP searches

Extra slides

Low Threshold Gas Detectors

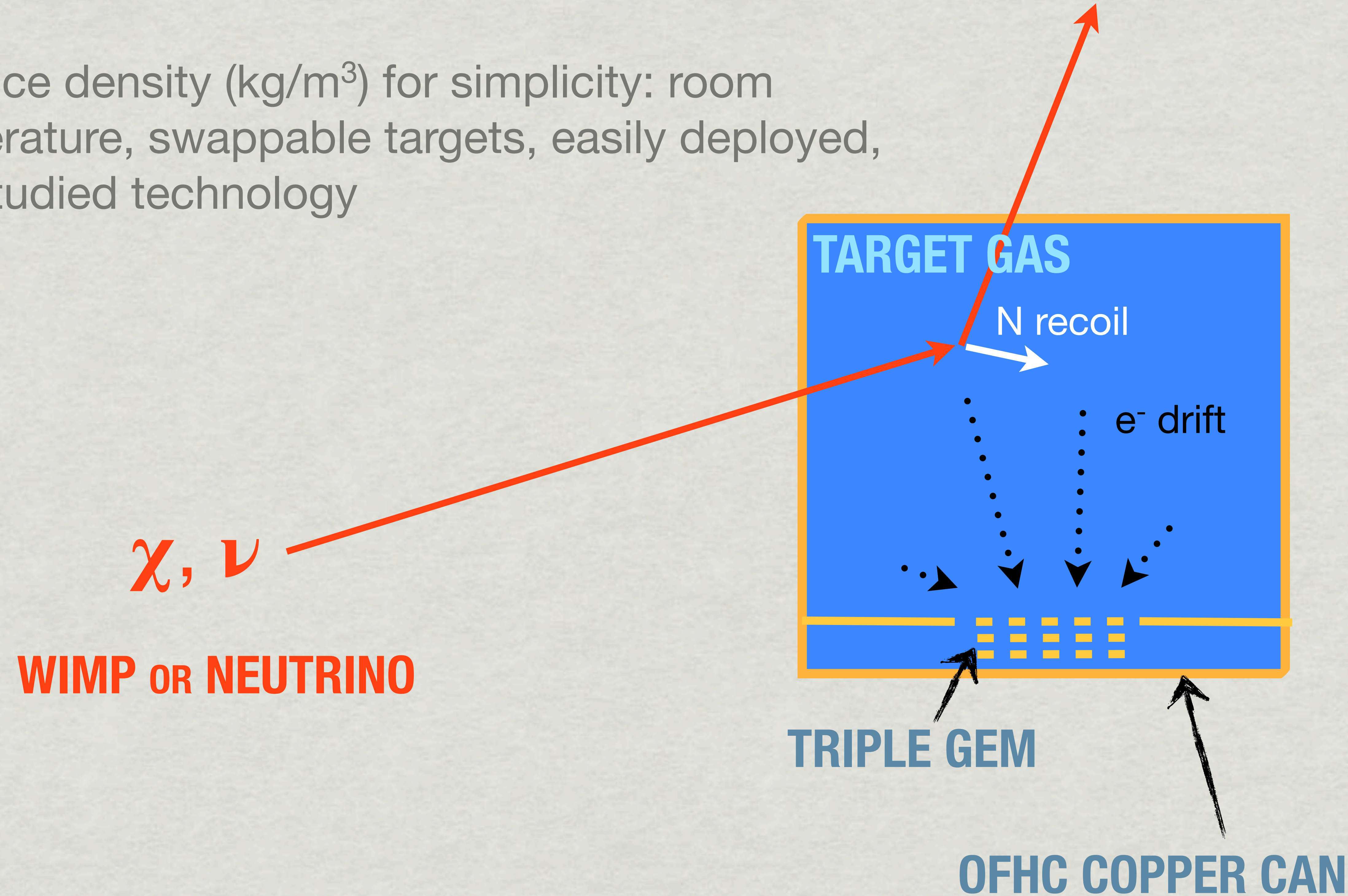
- Single electron sensitivity demonstrated (10's eV threshold)



P.S. Barbeau, J.I. Collar et al., NIM A515:439– 445, 2003.

Low Threshold Gas Detectors

- Sacrifice density (kg/m^3) for simplicity: room temperature, swappable targets, easily deployed, well studied technology



Precision Test of the Weak Nuclear Charge

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi}((G_V + G_A)^2 + (G_V - G_A)^2(1 - \frac{T}{E_\nu})^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2})$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

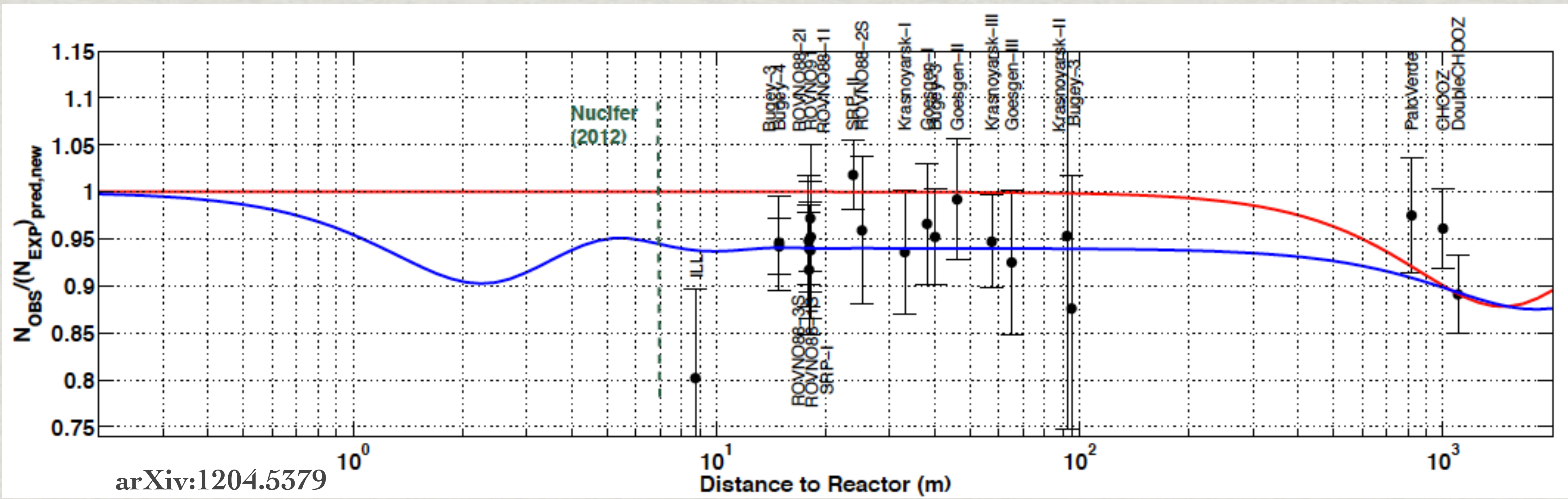
$$G_A = ((g_a^p + 2\epsilon_{ee}^{uA} + \epsilon_{ee}^{dA})(Z_+ - Z_-) + (g_a^n + \epsilon_{ee}^{uA} + 2\epsilon_{ee}^{dA})(N_+ - N_-))F_{nucl}^A(Q^2)$$

$$g_V^p = \rho_{\nu N}^{NC}(\frac{1}{2} - 2\hat{\kappa}_{\nu N}\underline{sin^2\theta_w}) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR}$$

$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}$$

+ axial vector factors which have more theoretical uncertainty (strong quark contributions, weak magnetism term, effective neutrino charge radii)

...for sterile ν searches



- Short baseline Rx experiments: apparent deficit of anti-ν_e's → possible indication of new physics: $\nu_{sterile}$'s with $\Delta m^2 \sim 1$ eV^2 or Rx flux uncertainties
- A short baseline **neutral current** experiment may help with the **"Reactor Anomaly"**

A. Drukier & L. Stodolsky, PRD 30 (84) 2295
C. Giunti and M. Laveder, arXiv:1109.4033 (2011)

...for ν magnetic moment searches

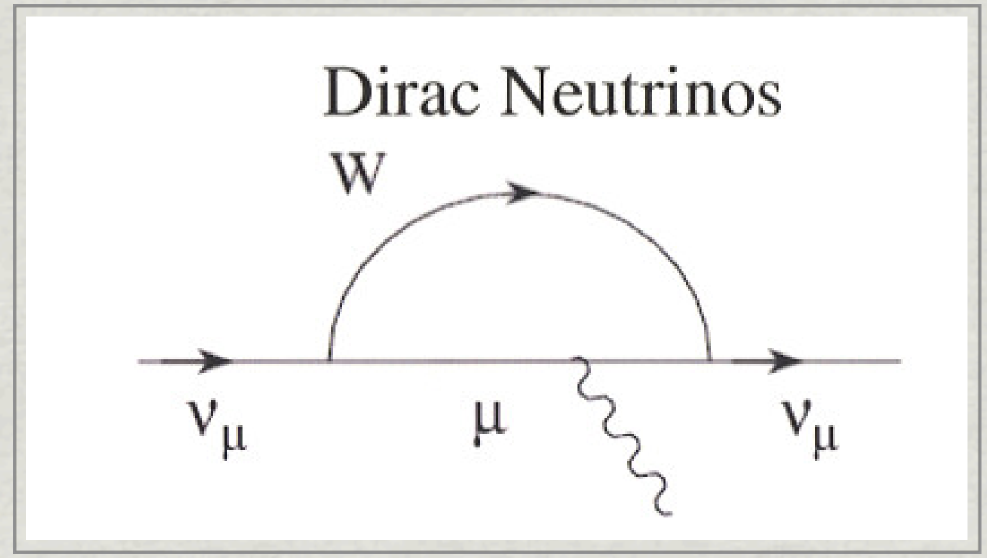
- Massive ν's → small Dirac μ_ν's

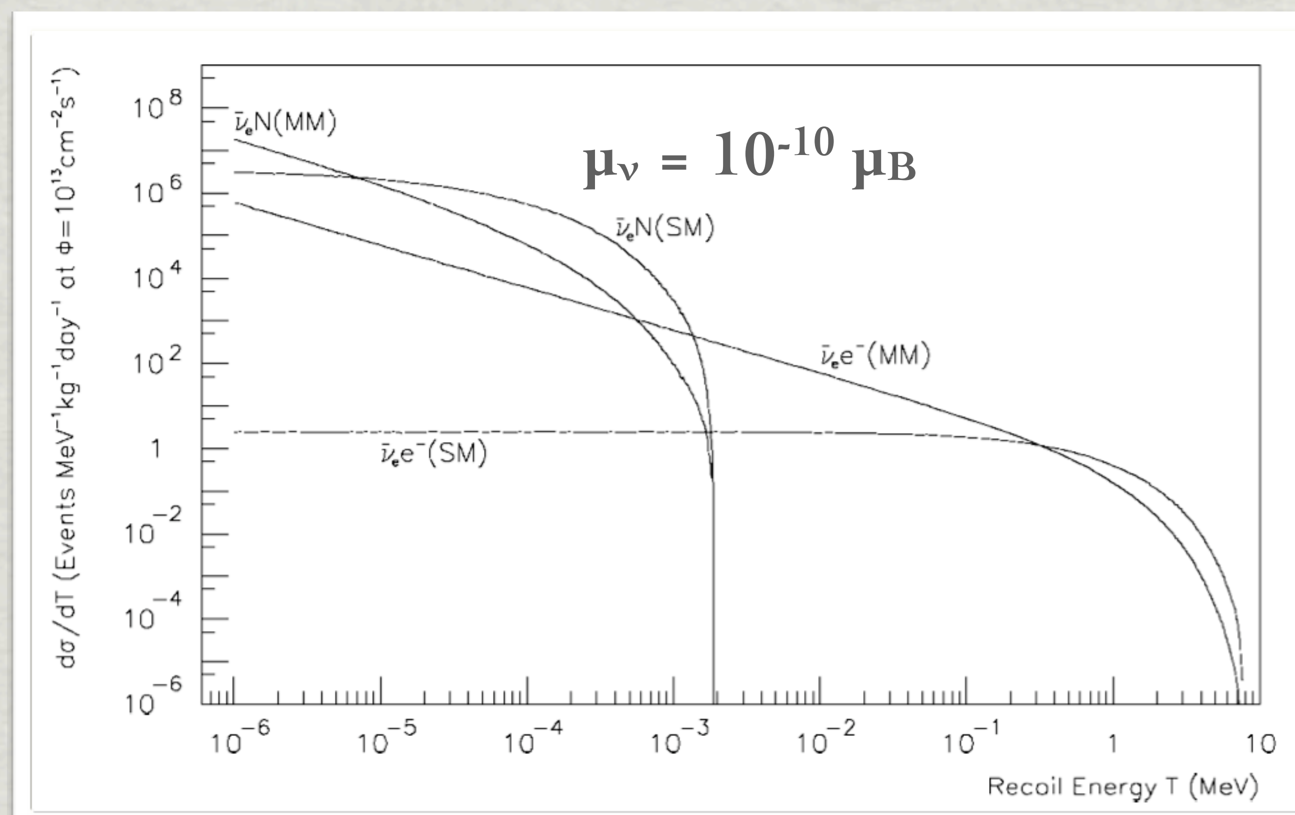
$$\mu_\nu \sim 3 \times 10^{-19} \mu_B \frac{m_\nu}{1\ eV}$$

- Some **Supersymmetric models**, models with **Large Extra Dimensions**, **right-handed weak currents** and **Majorana transition moments** can give rise to (detectable) μ_ν's orders of magnitude larger

- Low threshold detector → high sensitivity (ν-e and coherent ν-nucleus channels)

A. C. Dodd, et al., PLB 266 (91), 434

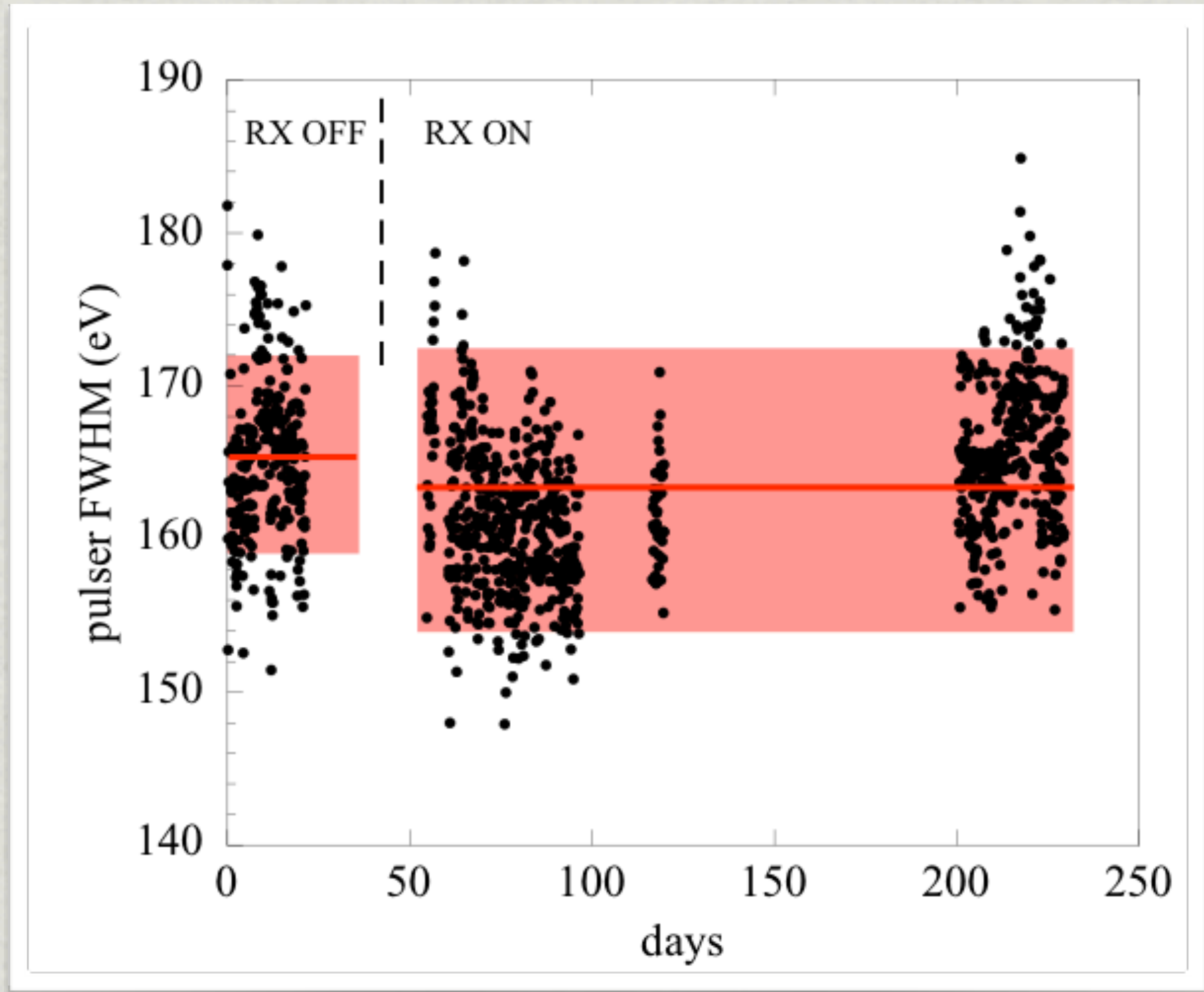




H. T. Wong and H.-B. Li. Mod. Phys. Lett., A20:1103–1117, 2005.

CoGeNT: ν dE/dx

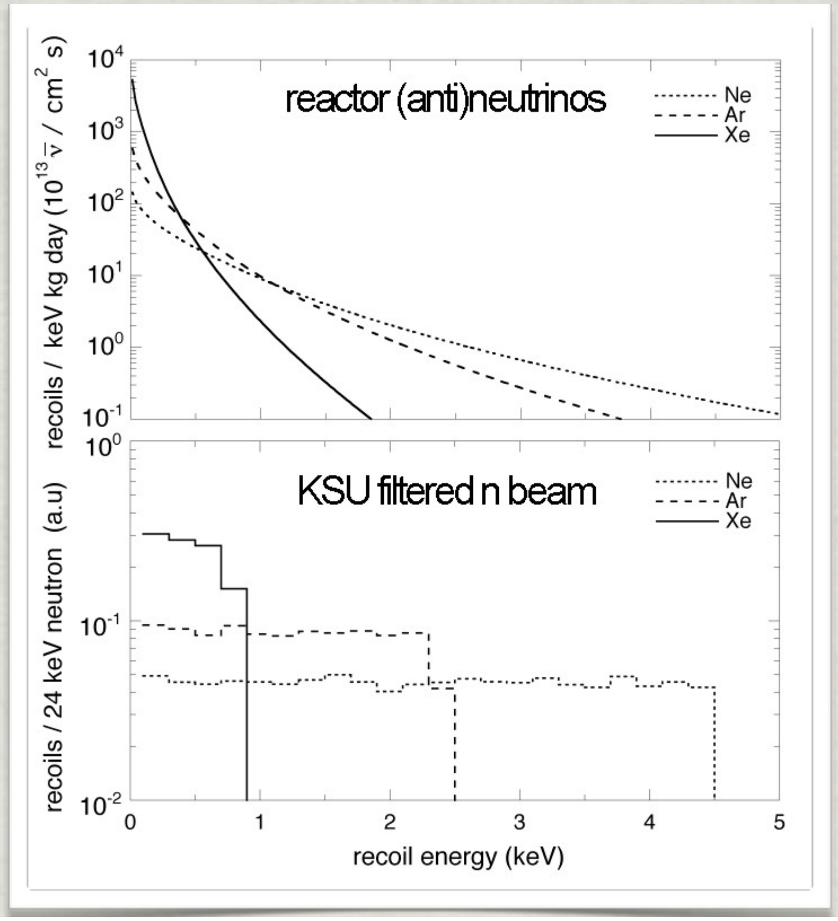
- By monitoring leakage current, we can constrain the ν dE/dx from large flux of Rx neutrinos (~10^{13} ν's cm^{-1} s^{-1})
- dE/dx < 4.6 x 10^{-8} eV cm^{-1}
- ~ 200 improvement over previous result (at one time, this was a possible explanation of the solar neutrino problem)

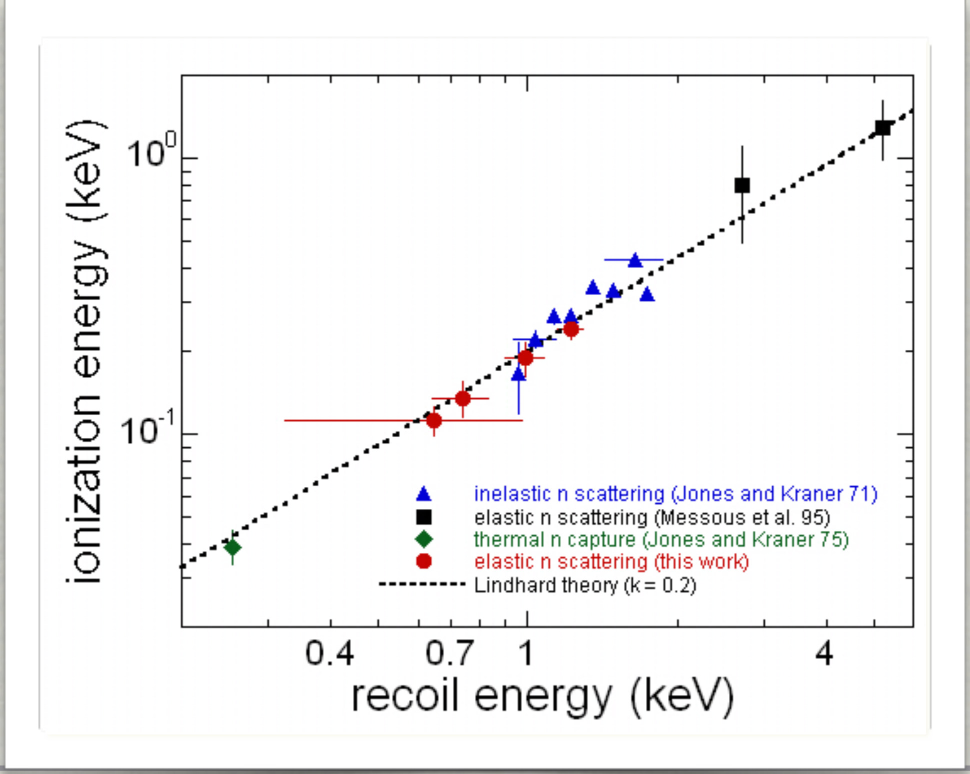


F. Vannucci , Nucl Phys. B 70 (1999) 199-200;
A. Castera *et al., Phys. Lett. B 452 (1999) 150-154*

CoGeNT: Importance of Calibrations

- Low energy nuclear recoils only deposit a fraction of their energy in the form of ionization (e.g. Quenching Factor ~ 20% for germanium)
- Developed a monochromatic 24 keV neutron beam at the KSU TRIGA reactor
- These neutron recoils mimic those expected from Rx ν's
- 10% uncertainty good enough for first measurement, but not for precision physics





P. S. Barbeau, J. I. Collar, Nucl.Instrum.Meth. A574 (2007) 385-391.
P. S. Barbeau, J. I. Collar, and O. Tench., JCAP, 2007(09):009, 2007.